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LCLS-II-HE CRYOMODULE TESTING AT FERMILAB*

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Abstract

22 Linac Coherent Light Source II (LCLS-II) cryomodules were successfully tested at the Cryomodule Test Facility (CMTF) at Fermilab. Following the completion of the LCLS-II testing program, CMTF has shifted to testing cryomodules for the LCLS-II High Energy upgrade (LCLS-II-HE). The first LCLS-II-HE cryomodule, the verification cryomodule (vCM), was successfully tested and verified the readiness of LCLS-II-HE cryomodule testing at CMTF, and production cryomodule (CM) testing has begun. Presented here are the production CM test acceptance criteria, testing plan, and CM test results so far.

LCLS-II HIGH ENERGY UPGRADE

Having concluded the LCLS-II test program, Cryomodule Test Stand 1 at CMTF is now fully dedicated to LCLS-II-HE CM testing. The infrastructure of the test stand remains largely unchanged. Eight, 7 kW solid state amplifiers have replaced the 4 kW amplifiers used during the LCLS-II test program, which were installed and commissioned during the final LCLS-II CM test. An EPICS-based controls system has also been implemented to conform with a model like what is used for the accelerator controls at SLAC. CMTF houses a state-of-the-art cryogenic facility with a cryogenic capacity of 500 W at 2 K [1].

ACCEPTANCE CRITERIA

The acceptance criteria have been slightly modified to accommodate for the increase in nominal gradient but remains similar otherwise. The 1.3 GHz, 9-cell cavities for LCLS-II-HE now use a 2/0 nitrogen doping recipe, with a nominal gradient of 20.8 MV/m. Fig. 1 gives an overview of some of the acceptance criteria parameters and Table 1 shows some key differences with respect to LCLS-II.

Table 1: Key Parameter Differences

Parameter	LCLS-II	LCLS-II-HE
Nominal Cavity Gradient [MV/m]	16	21
Max. Cavity Gradient [MV/m]	21	26
Min. CM Voltage [MV]	132	173
Multipacting Processing [Days]	1-2	4-5

Parameter	Value	Minimum acceptable performance during test
Minimum usable gradient for an individual cavity	16 MV/m	Usable gradient – the maximum gradient at which the following 3 conditions are met: • radiation level is below 50 mR/hr, • the cavity can run stably for one hour • 0.5 MV/m below the quench field.
Nominal usable gradient	20.8 MV/m	Individual cavities should reach a nominal usable gradient of 20.8 MV/m.
Minimum Usable CW voltage produced by an individual cryomodule	173 MV	The total CW voltage produced by cryomodule with cavities running at their usable gradients shall be ≥173 MV with all cavities powered simultaneously in GDR/SELAP mode and with the magnet at nominal operating currents for at least one hour with the dark current <30 nA. Additionally, the individual cavity gradients during this run must be recorded.
Stable Operation		For cavities that have a usable gradient above 20.8 MV/m, they must also be shown to be stable (no quenches or trips) at 20.8 MV/m for at least one hour.
Captured dark current	<30 nA	The dark current as measured by Faraday cups at each end of a cryomodule at the minimum CW voltage as defined above shall be ≤30 nA when the cavities are operated in GDR/SELAP mode with the relative phases set to accelerate speed of light electrons. This should be done in such a way to maximize the dark current measured at the Faraday cups.
Individual cavity Q_0		Individual cavity Q_0's must be measured at the expected operating gradient (20.8 MV/m or the usable gradient whichever is lower)
Cryomodule operating duration with RF power during test		Each cryomodule must operate at the minimum CW voltage or greater in GDR/SELAP and with the magnet at operating currents until the coupler temperatures achieve equilibrium or for a minimum of ten (10) hours with 90% operating time, whichever is less, to verify stable operation and confirm acceptable coupler heating.
2 K Dynamic Load at 173 MV voltage		The measured dynamic 2 K heat load of the cryomodule while operating at at total voltage of 173 MV must be ≤ 137 W (equivalent to an average Q_0 of 2.7×10^{10}).
Static heat load at 2 K		The static heat load at 2 K must be ≤7 W
Cryomodule thermometry		All installed thermometry shall be verified functional by observing consistency in output with operational conditions. For sensors measuring identical locations on components within a cryomodule there shall be variation of no more than 0.2 Kelvin under the same conditions at each component and under static load with no power applied to the cavities or magnets
Cavity Microphonics	<10 Hz peak to peak	The microphonics for each cavity must be 10 Hz peak to peak or less, measured over a 1 hour period while at the operating gradient with the JT valve regulating the liquid level (not in a locked position).
Cryomodule liquid level sensors		Liquid level sensors shall be verified functional by observing liquid levels and changes therein consistent with liquid supply rates and estimated boil-off rates
Cryomodule cryogenic valving		JT valve, CoolDown/Warm up, Bypass valves shall all be verified functional during cryomodule operations by consistency with expectations for operational performance, in particular, no valve or actuator is to have ice form on the room temperature components.
Cavity tuning to resonance during test (coarse tuner)		After cool-down to 2 K, each cavity must be able to be tuned to a resonant frequency of 1300.000 MHz. The tuner on the cavity #1 must be able to change the cavity's frequency from 1299.980MHz to 1300.020MHz. Tuners on cavities #2- #8 must be able to adjust cavity's frequency from 1299.535 MHz to 1300.020MHz.
Fine tuner minimum range	0-500 Hz	

Figure 1: LCLS-II-HE acceptance criteria.

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CRYOMODULE TEST PROGRAM

Aside from extra time allotted for multipacting (MP) processing, the installation, testing schedule, and removal remain largely unchanged to that of LCLS-II.

CM Test Sequence

The CM test sequence is approximately:

- Installation – 11 days
- Cooldown, 24hr soak at 2 K – 5 days
- Power rise, MP processing – 5 days
- Thermal cycle/fast-cooldown – 1 day
- Q_0 measurements – 2 days
- Unit Test – 1 day
- Pre warmup review, warmup, removal – 4 days

This test sequence is nearly identical to the LCLS-II testing program and has been described previously [2]. Due to the anticipation of MP processing, CM testing throughput at Fermilab has increased from ~39 calendar days per CM to up to ~50 calendar days.

Multipacting Processing

The MP-band for 1.3 GHz, 9-cell elliptical cavities of the type used for LCLS-II and LCLS-II-HE lies within a range of ~ 17-23 MV/m. This presents a challenge to testing and operation as the nominal gradient (21 MV/m) lies within the band. For this reason, it is critical to process MP to achieve stable operation. Experience testing a prototype CM, the vCM, and the first production CM at Fermilab, F1.3-21 (F21), has confirmed the need for MP processing and has helped to refine the MP processing test plan.

As seen both during cavity testing at Fermilab's Vertical Test Stand (VTS) and at CMTF, MP typically presents as radiation spikes, sporadic quenching, or a combination of the two during the initial power rise or power rise to max. gradient. Upon returning RF power to the cavity, the cavity may quench immediately or maintain field for some duration and then quench again. Figure 2 shows an example of MP processing for a LCLS-II-He cavity.

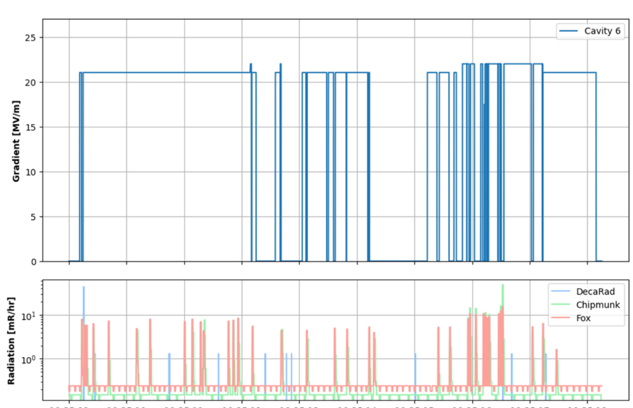

Figure 2: MP Processing – Cavity gradient (above) and radiation (below). Here one can see a quench followed by a stable run for approximately 2hr before repetitive quenching and processing.

In Fig. 2 one can see repetitive quenching in which the gradient (blue trace) falls quickly to zero as the quench interlock is triggered. The green, red, and yellow traces represent radiation spikes on three different radiation monitors: Mobile FOX units and DecaRad detectors for x-rays, Chipmunk detectors for gamma ray and neutron radiation.

The procedure for MP processing is as follows: increase the gradient until the cavity quenches, restore RF power to the cavity after quench, verify that the duration between quenches is increasing or become stable, and finally repeat this process and incrementally increase the gradient until the quench field or admin. limit (26 MV/m), whichever comes first.

Since the nominal gradient for operation lies within the MP-band, careful attention to the nominal gradient has been taken. Some cavities can be powered directly up to the admin. limit without quenching and some sit stably for several minutes or tens of minutes at gradient before quenching. Therefore, extensive testing at 21 MV/m is performed. It has been seen that a cavity may even run for over an hour without radiation, or with low-level radiation spikes and no quenching, and then a MP-induced quench takes place.

It is critical to avoid quenching prior to measuring Q_0, which is preceded by a thermal cycle and fast-cooldown from 50 K to 2K, as trapped flux can degrade this parameter. After processing up to the max. gradient, and prior to the thermal cycle/fast-cooldown, cavities are run individually, and later concurrently, at 21 MV/m for up to 4 hours.

CM TEST RESULTS

As of July 2022, two CM have been fully tested at Fermilab and both have met or exceeded the test criteria and results will be presented here.

MP has been observed in many of the 16 cavities tested. Field Emission (FE) has only been observed in three cavities so far: one cavity from the vCM had < 5 mR/hr radiation, which was fully processed during the Unit Test, and two cavities F21 – both of which were below the 50 mR/hr limit at nominal gradient.

Verification Cryomodule

vCM installation began in March 2021 and was tested extensively from April 2021 through October 2021. There were three stages of testing with this CM:

1. Initial testing: April – May
2. Re-test after coupler fix: May – June
3. Re-test after plasma processing: October

During Stage 1 of testing, it was discovered that there was an issue with the fundamental power coupler of cavity 1. It was decided to proceed with initial testing on the remaining seven cavities before warming the CM to repair the coupler. Upon inspection, the antenna screw of the inner conductor had not been fully torqued. No damage was observed, and the coupler was then reinstalled.

Stage 2 of testing included the full suite of tests from the testing sequence, including an extended Unit Test. Nomi-

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nally, a Unit Test consists of powering all cavities to nominal gradient for 10-12 hours. For the vCM, testing was instead carried out for 8 consecutive days to mimic linac operation.

After the second stage of testing, the vCM was warmed to room temperature and plasma processing was performed on 4 of the 8 cavities. The CM was then cooled and the full suite of tests were once again performed, aside from a second Unit Test. Re-testing showed that cavity performance did not suffer after processing. It should also be noted that the 4 cavities which were processed did not exhibit MP quenches or radiation. Details of the vCM results and plasma processing can be found in Refs. [3] and [4].

First Article Cryomodule

The First Article CM, F21, is the first LCLS-II-HE production CM. It was installed in March 2022, tested through April and May, and removed in June. The CM qualified and all cavities were within spec aside from two parameters.

Three cavities in this CM produced Q_0 measurements below spec., which resulted in an average Q_0 below 2.7e10. This resulted in nonconformance for 2 K dynamic heat load – the spec is ≤ 137 W, F21 measured 151 W at 21 MV/m. This nonconformance may lie in the fact that these three cavities were left over from LCLS-II and, despite being within spec in vertical testing, were not the new 2/0 doped LCLS-II-HE cavities.

Cavities 1-3 also exhibited nonconformance in that microphonics measurements resulted in a detune frequency above the 10 Hz limit.

Cavity 1 and 6 exhibited FE, however the radiation was within spec at nominal gradient.

Experience gained from MP studies with the vCM helped to refine a plan for processing, resulting in F21 cavities exhibiting no MP after the thermal cycle and fast cooldown.

CM Test Results

Figure 3 shows test results from the first to LCLS-II-HE CM tests. Table 2 provides several key test parameters with a comparison to specification.

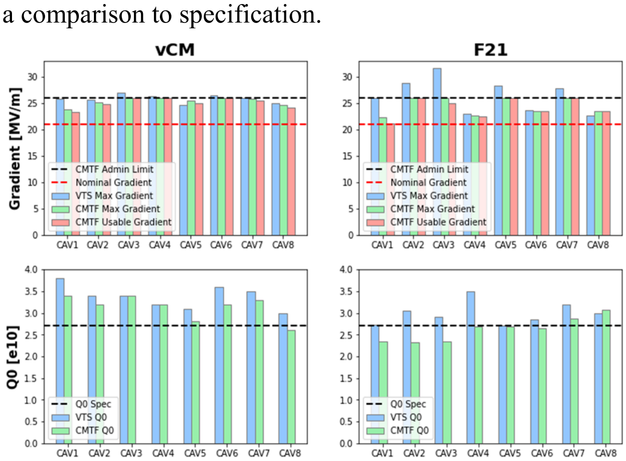

Figure 3: Gradient and Q0 comparison between VTS and CMTF tests for the vCM and F21.

Table 2: vCM and F21 CM Test Results

Parameter	Spec	vCM	F21
Average Q_0 @ 21 MV/m [e10]	2.7	3.12	2.62
2 K Heat Load @ 21 MV/m [W]	< 137	119	141
Max. CM Voltage [MV]	N/A	211	203
Usable CM Voltage [MV]	173	208	201
Field Emission @ 16 MV/m [mR/hr]	< 50	0	1

CONCLUSION

Following the successful completion of the LCLS-II CM test program, two LCLS-II-HE CM have been tested and qualified at Fermilab.

With a test stand fully dedicated to LCLS-II-HE, a prototype CM has been tested with world record performance for a CW machine. The success of this test validated cavity performance for the vendor as well as Fermilab's readiness for the LCLS-II-HE program.

The first production CM, F21, has also been tested and qualified, kicking off the production schedule for the remaining 12 CM.

The next production CM, F1.3-22, is scheduled to be installed in early August 2022 and from here the ~50 calendar day test cycle will begin.

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